Conjunction Sensitivity to Atmospheric Density Modeling

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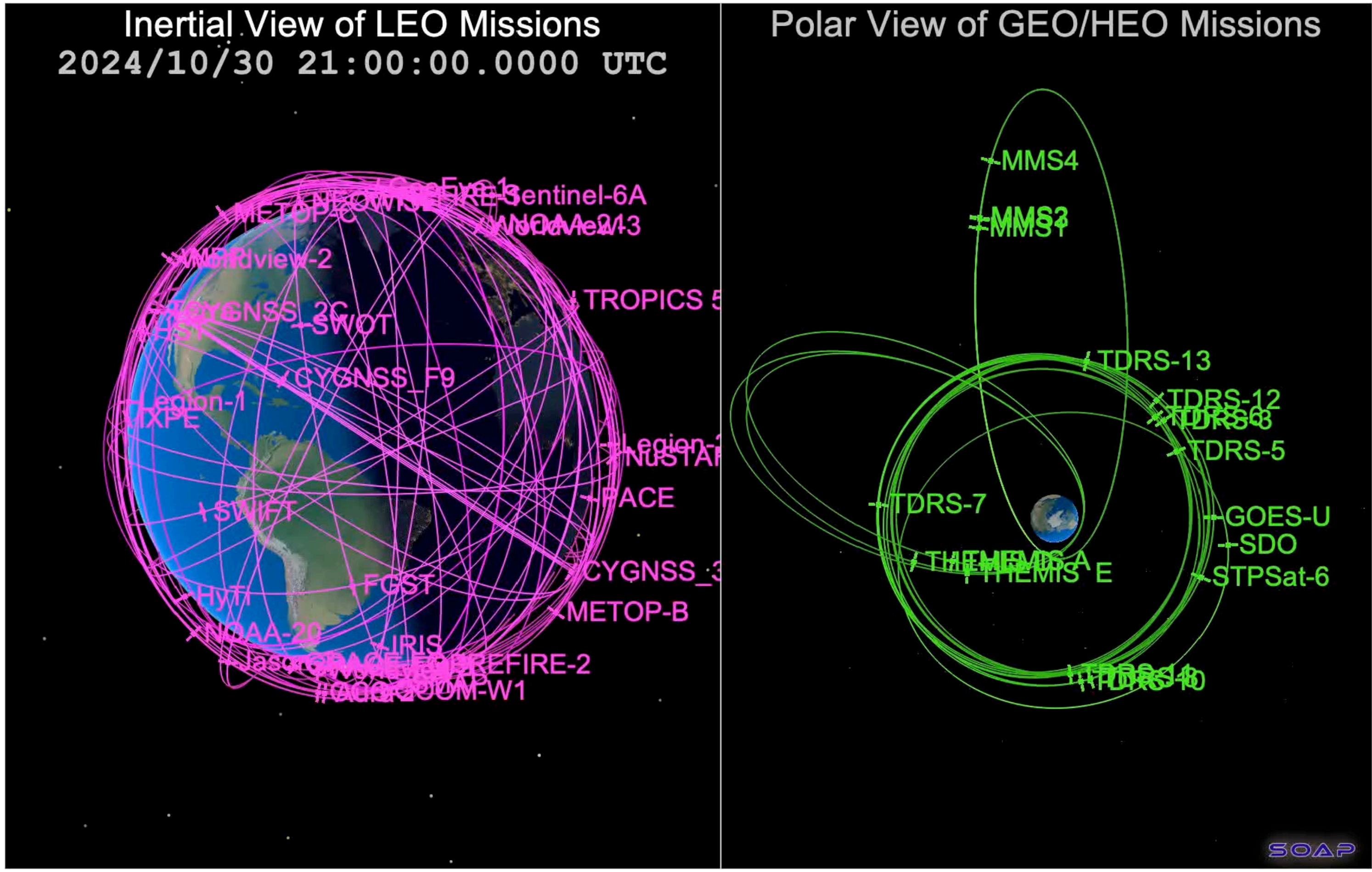
Agenda

- **Conjunction Assessment Overview**
- **Ephemeris Generation**
- **Probability of Collision Sensitivity to Density Accuracy & Uncertainty**
- **Conclusion & Way Forward**

NASA Conjunction Assessment Risk Analysis (CARA) Overview

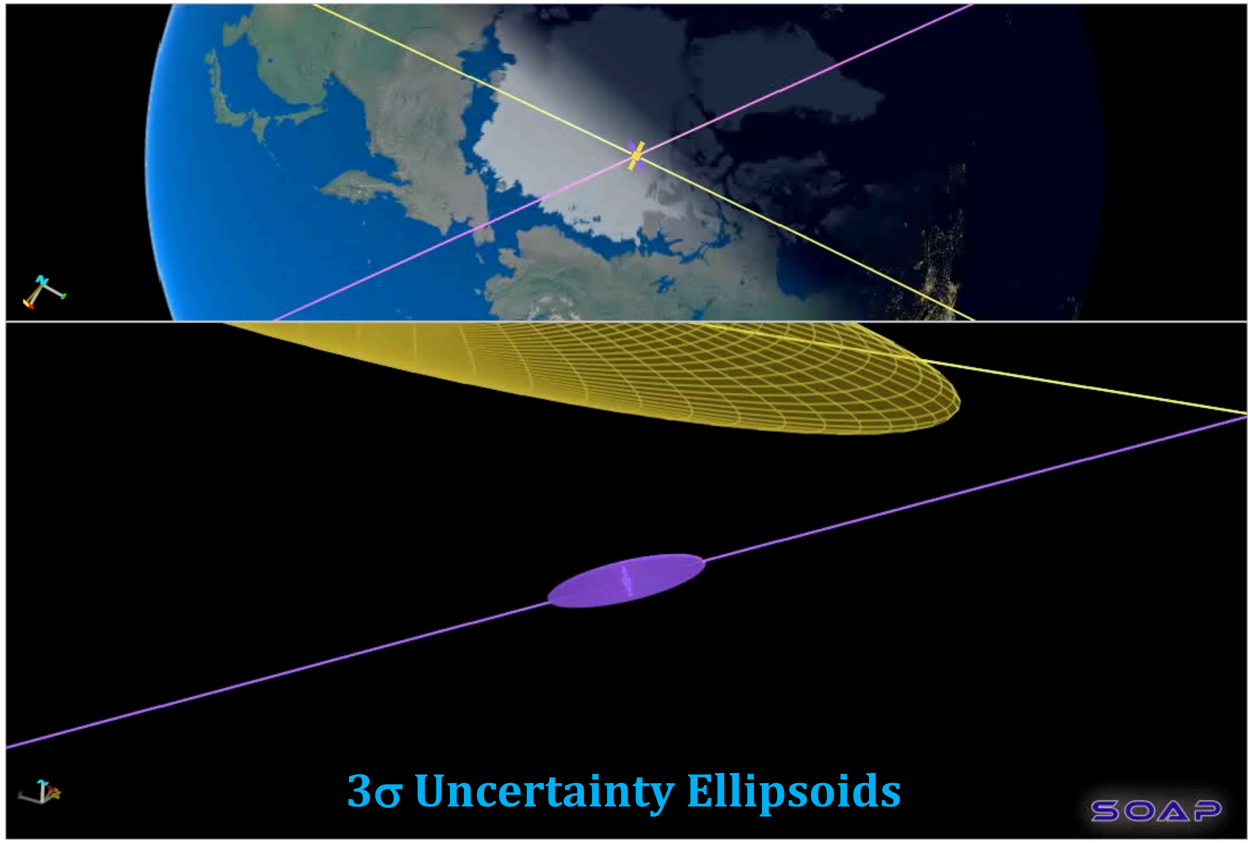
- **CARA provides conjunction risk analysis support to all operational NASA uncrewed missions**
  - –Supports ~80 missions in different orbit regimes
- **Provides service to other agencies**
  - –NOAA, CNES, etc.



- **CARA supports many mission affected by drag**

Probability of Collision (Pc)

- **CARA screens fleet against resident space object (RSO) catalog for close approaches**
- **Risk expressed as Pc**
  - Likelihood that, given the uncertainties in the two satellites' predicted trajectories, actual miss distance will be less than combined size of satellites
- **Both propagation <u>accuracy</u> and <u>uncertainty</u> are important**



- **Example:**
  - Close approach distance = 185 m
  - Pc = 9.51E-04 (1 in 1051)

Ephemeris Generation

- **Two ephemeris sources for CARA supported missions:**
  – USSPACECOM high accuracy catalog (HAC) (all missions)
  – Owner/operator (O/O) navigation teams (maneuverable missions)
- **Various tools & mission requirements**
  – e.g., gravity recovery (precision OD) vs. astronomical observatory (precision pointing)
  – Some missions' performance driven by conjunction assessment requirements
- **Accurate conjunction assessment requires *prediction* accuracy**
  – Position & velocity at TCA with realistic covariance that fairly represents expected uncertainties
  – For LEO satellites, neutral density models drive both prediction accuracy and covariance realism

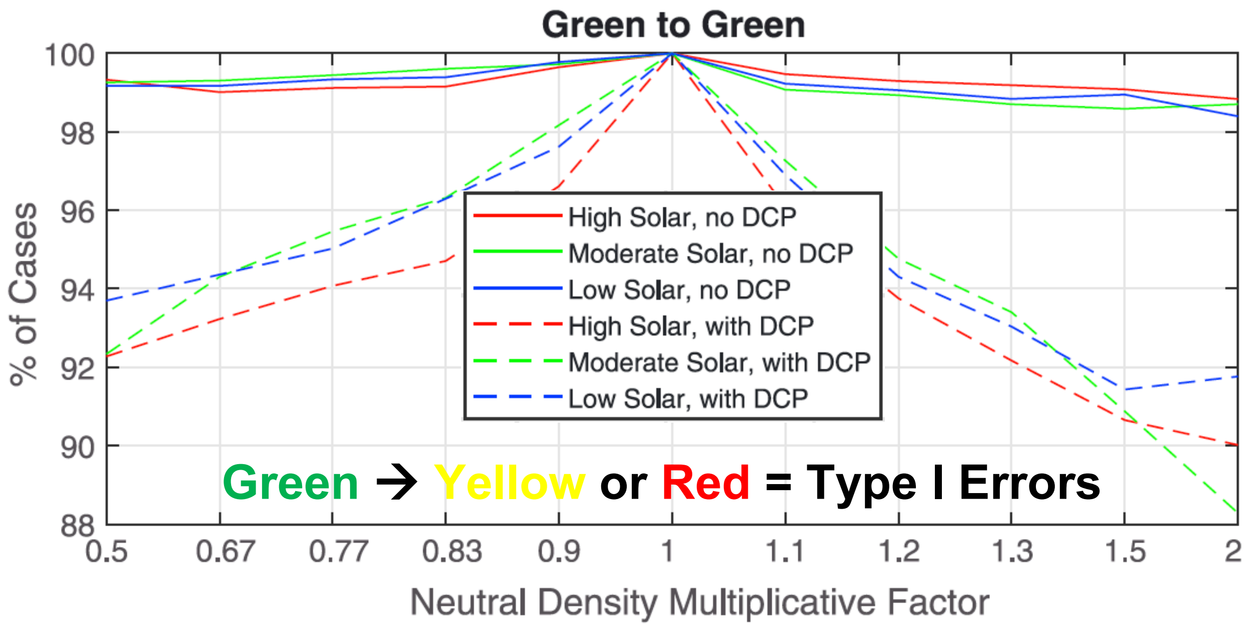
State Estimate Errors: Atmospheric Drag

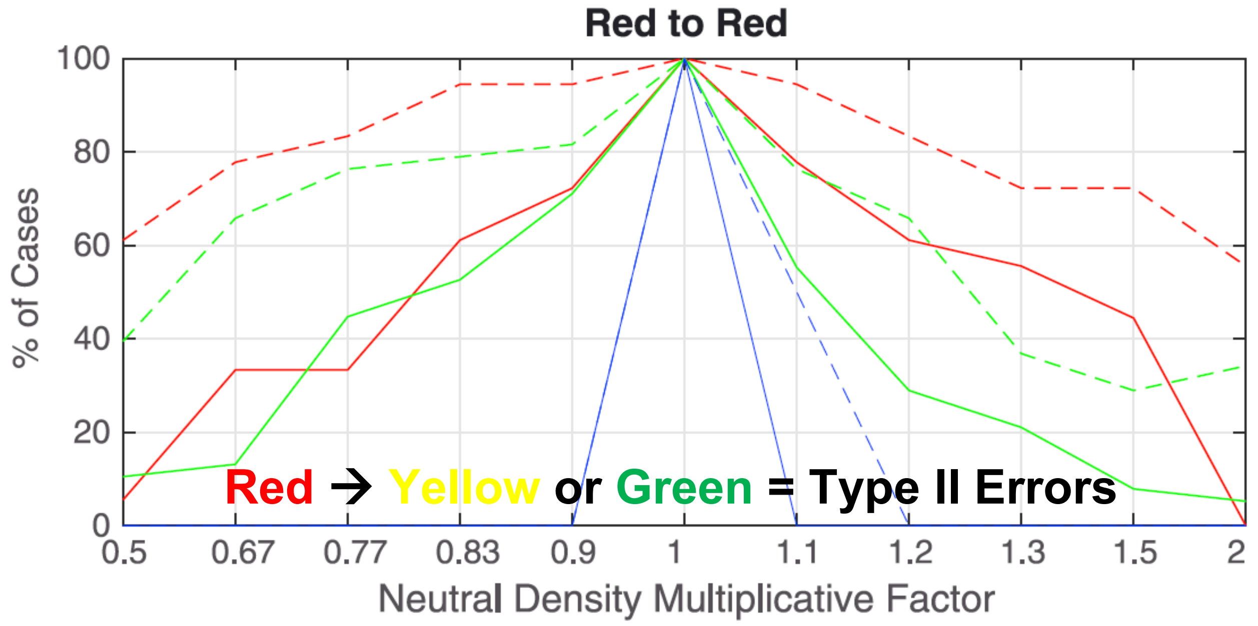
- **Atmospheric drag magnitude:** $a_{drag} = \frac{1}{2}\beta\rho v^2$
- **Ballistic coefficient (*β=C_DA/M*) solved for in OD; included in covariance**
  - Accounts for errors in *C_D, Area, Mass, and ρ by scaling entire drag acceleration*
- **Errors in *ρ* can be considerable**
  - In general not characterized well and not separately included in covariance
  - Some improvement with inclusion of dynamic consider parameter (DCP) in covariance to compensate for atmospheric density prediction error
- **Errors in *ρ* become drag acceleration errors, which cause in-track (primarily) and radial (secondarily) errors in the orbit**
- **While state estimate accuracy desirable, probably more important to conjunction assessment to have good state error estimate**
  - With this, meaningful Pc can be calculated and enable decisions
- **Increased focus needed on density model error analysis**

Atmospheric Density Error Experiment: Effect on Calculated Pc

- **Reprocess historical conjunctions, introducing error into ρ**
  - Reduce and increase *ρ* by up to 100%
- **Observe change in calculated Pc, in two modes**
  - Covariance unaltered
  - Covariance altered to account for introduced error
    - Emulates case in which expected error in *ρ* known
- **Best way to summarize results is by event "color," which gives severity**
  - **Red**: Pc => 1E-04; most serious event—remediation usually pursued
  - **Yellow**: 1E-07 <= Pc < 1E-04; can become serious—event monitored
  - **Green**: Pc < 1E-07; event essentially ignored
- **Event color changes examined as error in *ρ* introduced**
- **Effect on event stability if amount of *ρ* error known *a priori***

Density Error Effect on Pc: Experimental Results





- **Type I error: green events that, with error, misclassified as yellow or red ("false alarm")**
  - Percent of affected events small (only a few percent)
  - Compensated covariance produces more deviation, but at least in conservative direction

- **Type II error: red events that, with error, misclassified as green or yellow ("missed detection")**
  - Uncompensated covariance pushes a larger number to green or yellow
  - Much more problematic, as these events not likely to be remediated

Density model accuracy matters significantly, but knowledge of model error can blunt effect substantially

Image credit: Hejduk, M. D., & Snow, D. E. (2018). The effect of neutral density estimation errors on satellite conjunction serious event rates. Space Weather, 16. https://doi.org/10.1029/2017SW001720

Conclusion

- **Conjunction assessment mission substantially affected by accuracy of atmospheric modeling**
  - More accurate modeling allows more actionable Pc
- **However, simply knowing expected model error allows error compensation and both a correct and more stable Pc**
- **Important to pursue both, but accuracy improvements without error statement much less useful than if active error modeling included**

Way Forward

- **Develop error budget for density prediction**
  - –Quantitatively account for uncertainty in each contribution to enable roll-up of a total density uncertainty value
    - Distinguish biases from time-dependent errors (i.e., rates of error growth)
    - As modeling improvements are made to a specific contributor, its error budget amount can be reduced
  - –Include solar & geomagnetic indices/proxies, winds, atm constituents, etc.
- **Result could be separately accounted in drag uncertainty**
  - –Spacecraft team would provide uncertainty on ballistic coefficient, strictly for uncertainties in C_D, area, and mass (i.e., not a *drag* scale factor)
  - –Would enable more refined tuning of predicted covariance to achieve better realism

Conjunction Assessment Risk Analysis

NASA CARA

PREDICT—ASSESS—MITIGATE

Questions?

Conjunction Event Pc Progression

- **Conjunction usually first discovered 7 days before time of closest approach (TCA)**
  - Covariances large, so typically Pc well below maximum (**A**)
- **As event tracked and updated, changes to state estimate are relatively small, but covariance shrinks**
  - Because closer to TCA, less uncertainty in projecting positions to TCA (**B**)
- **Theoretical maximum Pc encountered when 1-sigma covariance size to miss distance ratio is $1/\sqrt{2}$ (C)**
  - After this, Pc usually decreases rapidly (**D**)
- **Improving position accuracy thus has effect on Pc that is difficult to predict**
  - More accurate calculation, but Pc could increase or decrease
  - <u>Covariance</u> <u>realism</u> critical for accurate calculation of Pc

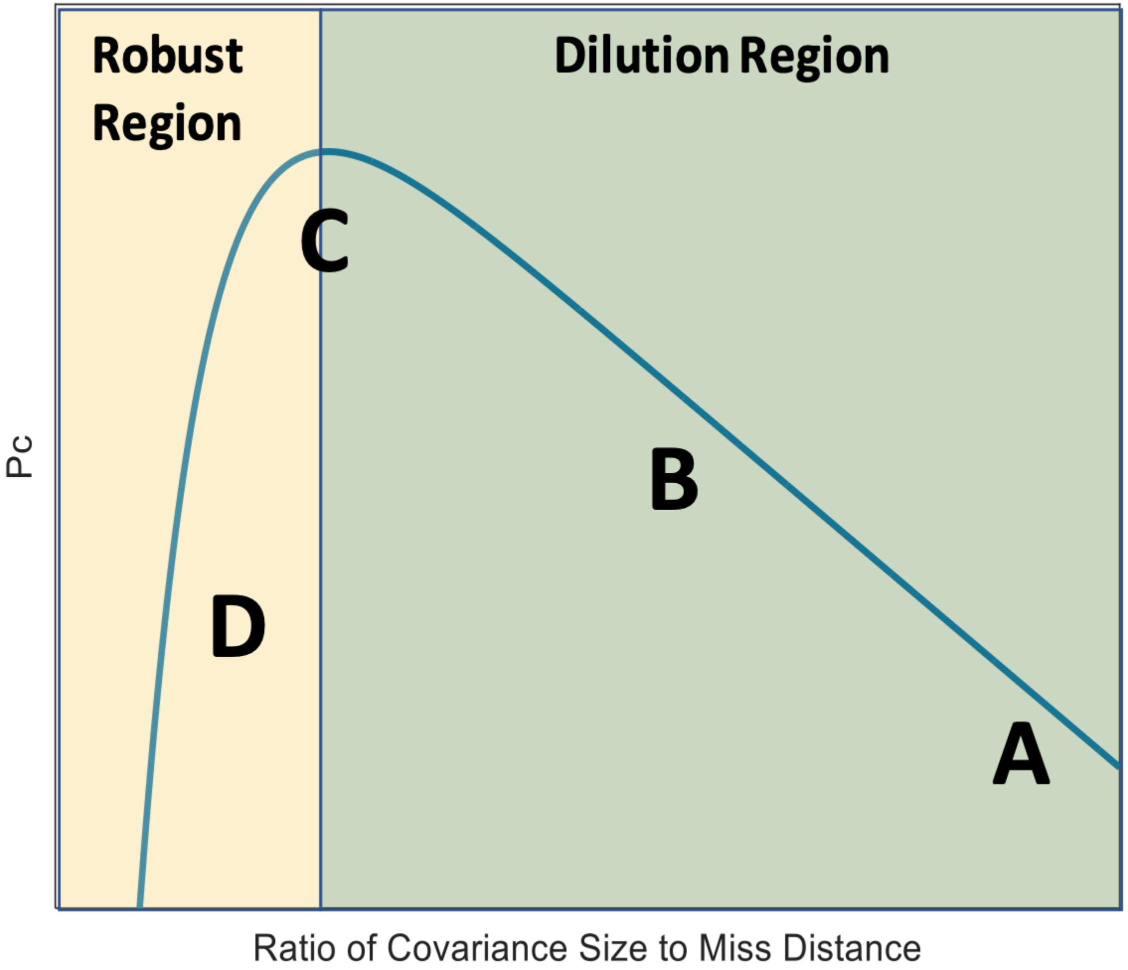


Image credit: M. D. Hejduk and D. E. Snow, "Setting the Bar for the Replacement of the Probability of Collision Metric," 29th International Symposium on Space Flight Mechanics, Darmstadt, Germany, 22– 26 April, 2024.